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JOINTLY CONTROLLING TRANSMISSION RATE AND POWER IN A COMMUNICATIONS SYSTEM

This application claims the priority under 35 U.S.C. § 119(e)(1) of copending U.S. provisional application number 60/262,007 filed on January 16, 2001, and incorporated herein by reference.

FIELD OF THE INVENTION

The invention relates generally to communications systems and, more particularly, to controlling transmission rate and power in a communications system.

BACKGROUND OF THE INVENTION

Communications systems which employ wireless transceivers are well known. However, as is the case with most electronic technologies today, there is an ever-increasing demand to improve information transmission rates and reduce power consumption while, at the same time, reducing the influence of noise and improving the quality of transmission. A

fixed transmission power limits the transmission rate. The longer a transmission takes, the more power is consumed. Therefore, it is desirable to decrease the amount of time a given transmission takes. Additionally, different transmission rates affect the quality of the transmission. For example, higher transmission rates are more susceptible to noise. Increased noise results in decreased transmission rates.

Current communications systems control the transmission rate and the transmission power independently using two (2) control variables. One power control algorithm monitors network conditions. In response, the power control algorithm updates the power control variable at a regular interval. A separate algorithm monitors channel conditions to adjust the data rate. Neither algorithm can guarantee the highest possible transmission rate at the lowest possible transmission power, nor do the algorithms minimize the level of interference generated to other devices.

Wireless devices tend to interfere with one another due to reasons such as lack of mutual protocol, use of an unlicensed frequency band or use of a collision based access mechanism. An example of interference generated by lack of a mutual protocol is the simultaneous co-located use of Bluetooth and IEEE 802.11b devices. Neither device is able to directly communicate with the other, and their differing protocols result in packet collisions, which in turn results in lost data on both the Bluetooth and IEEE 802.11b

network. The use of unlicensed bands such as the 2.4GHz ISM band or the 5GHz U-NII band also results in devices that must contend for the wireless medium in an interference environment. In addition, some protocols, such as the IEEE 802.11 Distributed Coordination Function (DCF) channel access mechanism, yield environments where even IEEE 802.11 devices must tolerate interference from one another.

A wireless communications device must have a sufficiently large signal to noise ratio to decode a received packet correctly. Noise from various sources affects the receiver. This noise can be thermal noise that is generated in the receiver itself or it can be noise external to the receiver. Noise external to the receiver may come from other devices in the area. The amount of noise received from such devices depends on the amount of power such a device transmits, the path loss to the receiver and the amount of power transmitted by the interfering device. The amount of interference is thus reduced if the interfering device transmits less power and transmits less frequently.

Any wireless communications device is a potential interferer to other devices. To reduce the interference generated, the wireless device can reduce its transmit power level. However, there is a level below which the transmit power cannot be reduced, because below this level the device that is being transmitted to will no longer be able to decode the transmission successfully. Thus it is desirable to transmit at or just above this threshold to

minimize the amount of interference that other devices in the area experience as a result of the transmission.

In addition to power control, wireless devices may also control the rate at which they transmit. The rate of transmission controls the length of time that the wireless device must transmit. In packet-based systems such as wireless local area networks, transmission time includes of some fixed overhead typically including a preamble and header, and the payload. Thus the transmission time, t_{TX}, is equal to

$$t_{TX} = t_0 + N_b/R$$

where t_0 is the overhead time, N_b is the number of data bits in the packet and R is the transmission rate. Reduction of the amount of time, i.e. t_{TX}, that a wireless device transmits reduces the amount of interference to other devices. Increasing the transmission rate, R, reduces the transmission time. As the transmission rate, R, is increased, the received SNR threshold for the receiving device to properly decode the packet also increases. Depending on the transmit power and path loss, the transmitting device may or may not be able to transmit at its maximum rate, as the receiving device may not be able to decode at that rate. Wireless devices can control one or both of their transmission rate, R, and their transmit power level.

As illustrated by FIGURE 1, in typical wireless communications devices, an adaptive method **110** controls the transmission rate (R) **120** based on inputs **130** such as the measured packet error rate (PER) **130c**, signal to interference noise ratio (SINR) **130b** and signal to noise ratio (SNR) **130a**. In such wireless communication devices, e.g. 802.11 wireless LANs, the transmit power is fixed. At best, the transmit power may be changed via a user interface. It is not adaptively changed.

It is desirable in view of the foregoing to provide a solution that enables higher transmission rates at lower power levels and minimizes the level of interference generated. The present invention controls both the transmission rate and power level in a fashion that minimizes the level of interference generated by the act of transmission. The present invention enables enhanced coexistence of wireless devices via a joint transmit power and rate control scheme. By employing the present invention, wireless devices may reduce the level of mutual interference, thereby allowing improved performance.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and further advantages of the invention may be better understood by referring to the following description in conjunction with the accompanying drawings in which corresponding numerals in the different figures refer to the corresponding parts, in which:

FIGURE 1 diagrammatically illustrates controlling the transmission rate based on individual inputs in accordance with the prior art;

FIGURE 2 diagrammatically illustrates a portion of an 802.11 based system in accordance with the known art;

FIGURE 3 diagrammatically illustrates an adaptive joint transmission rate and power controller in accordance with an exemplary embodiment of the present invention;

FIGURE 4 illustrates 802.11b compliant device rate and power pairs in accordance with an exemplary embodiment of the present invention;

FIGURE 5A diagrammatically illustrates an adaptive joint transmission rate and power controller using PER as an input in accordance with an exemplary embodiment of the present invention;

FIGURE 5B is an exemplary flow diagram for FIGURE 5A;

FIGURE 5C diagrammatically illustrates part of FIGURE 8 in greater detail;

FIGURE 6A diagrammatically illustrates an adaptive joint transmission rate and power controller using PER and SNR as inputs in accordance with an exemplary embodiment of the present invention;

FIGURE 6B is an exemplary flow diagram for FIGURE 6A;

FIGURE 6C diagrammatically illustrates part of FIGURE 8 in greater detail;

FIGURE 7A diagrammatically illustrates an adaptive joint transmission rate and power controller using PER with a combination of SNR and SINR as inputs in accordance with an exemplary embodiment of the present invention;

FIGURE 7B is an exemplary flow diagram for FIGURE 7A;

FIGURE 7C diagrammatically illustrates part of FIGURE 8 in greater detail; and

FIGURE 8 diagrammatically illustrates a transmitting apparatus in accordance with exemplary embodiments of the present invention.

DETAILED DESCRIPTION

While the making and using of various embodiments of the present invention are discussed herein in terms of Bluetooth and 802.11b compliant devices, it should be appreciated that the present invention provides many inventive concepts that can be embodied in a wide variety of contexts. The specific embodiments discussed herein are merely illustrative of specific ways to make and use the invention, and are not meant to limit the scope of the invention.

The present invention provides a solution that enables higher transmission rates at lower power levels and can minimize the level of interference generated. The present invention can optimally control both the transmission rate and the transmission power using one variable in a joint rate shift and power control function. Additionally, the present invention can maximize channel capacity by minimizing the transmission time.

The dominant source of power consumption is the amount of time spent transmitting; the power level is less important. It can be assumed that it is better to transmit at a higher rate, even if it is at a higher power, than to transmit at a lower rate in order to save power. Therefore, some embodiments of the present invention first maximize the transmission rate and then lower the transmission power level while maintaining the transmission rate.

The present invention jointly controls rate and power in a fashion that enables control of the two variables in one dimension. In some embodiments, this is done by ordering the possible transmit rate and transmit power combinations in a logical sequence that meets specific conditions. The present invention can first minimize the transmit time and then reduce the transmit power. The present invention can maintain the maximum rate possible that enables the receiving station to decode packets with an acceptable probability.

Secondarily, the transmit power is minimized. The transmit power is only reduced from its maximum level when the maximum transmit rate is achievable. By reducing the transmit power, the level of interference to other devices in the area is reduced. The transmit power will generally not be reduced below the point that yields the lowest acceptable probability of reception error. When the error rate at the receiver exceeds a selected level, the transmit power should be increased, if possible, otherwise the transmit data rate should be reduced. These actions will reduce the probability of error at the receiver.

In an exemplary implementation of the present invention, the joint power control and rate control method is used in a communication system that includes a transmitting apparatus **210** and a receiving apparatus **220**. A portion of such a system is diagrammatically illustrated in FIGURE 2. Examples of the communication system of FIGURE 2 include Bluetooth and IEEE 80211.b systems. In an 802.11b system example, an Access Point (AP)

210 and station (STA) **220** communicate with one another. In this example, AP **210** transmits **215** to STA **220**. The rate of transmit **320** and power level **340** (FIGURE 3) are selected by AP **210**. As many thousands of packets may be sent per second, AP **210** and/or STA **220** can obtain good estimates of inputs **330**, such as SNR **330a**, PER **330c** and SINR **330b**, as shown in FIGURE 3. SNR **330a**, PER **330c** and SINR **330b** are used as inputs **330** to joint adaptive transmission rate and power control method **310** that is implemented by AP **210**. The method can be executed in a processor inside AP **210**. It may also be directly implemented as hardcoded logic gates.

Upon transmit from AP **210** to STA **220**, the SNR of the transmission is of interest. STA **220** has direct access to estimation of the SNR. AP **210** requires knowledge of the SNR as input **330a** to joint rate and power control method **310**. STA **220** may transmit this information to AP **210**, or AP **210** may calculate an estimate of SNR **330a** when STA **220** transmits to AP **210**. The same is true for SINR **330b**. PER **330c** can be estimated using the acknowledgement **225** packets that are sent back from STA **220** to AP **210** after transmission from AP **210**. This PER **330c** estimate is also used as an input **330** to joint rate and power control method **310**. Joint rate and power control method **310** selects a transmit power **340** and rate **320** pair from an ordered list. The ordered list is formed by listing all transmit rates from the least to the maximum along with the maximum transmit power, corresponding to

indices 1-5 of FIGURE 4 (discussed in more detail below). The list is then completed by listing the maximum transmit rate along with all transmit powers in decreasing order, corresponding to indices 6-9 in the example of FIGURE 4.

As an example, the Texas Instruments ACX100, 802.11b compliant wireless local area network processor contains data rates of 1, 2, 5.5, 11 and 22 Mbps. A typical radio may allow transmit powers of 1, 5, 10, 30 and 100 mW. In accordance with some exemplary embodiments of the present invention, to minimize the amount of interference produced while still maximizing throughput, the rate and power pairs are ordered as shown in the table of FIGURE 4. The index in FIGURE 4 is mainly to assist in further reference to movement in the table. However, such an index could be used in an implementation and mapped to the appropriate rate and power pairs. Some embodiments initially enter the table at index 5 in an attempt to maximize the data rate.

The present invention also has the advantage that not all rate and power pairs are possible. This helps to avoid the possibility of operating at a rate and power pair that is suboptimal, as can occur when separate, non-joint rate and power control algorithms are used. Additionally, the adjustment of the transmit rate and power level affects the inputs to the joint rate control and transmit power method at **310** in FIGURE 3. An increase in transmit power and/or decrease in rate tends to reduce the PER. Likewise a decrease in

transmit power and/or increase in rate tends to increase the PER. An increase/decrease in transmit power tends to increase/decrease the SNR.

Alternatively, the present invention can be implemented as shown in FIGURE 5A, with PER **530** as the only input. In this scenario, when PER **530** increases above a threshold, T_{PER}, adaptive rate and power control method **510** decreases the index of FIGURE 4, which in turn has the affect of decreasing PER **530**. Some embodiments increase the index into the table of FIGURE 4 when PER **530** is very low (below a lower threshold).

FIGURE 5B shows an exemplary flow diagram for the embodiment shown in FIGURE 5A. A determination is made in block **515** as to whether or not the PER is above an upper, predetermined threshold. If the PER is above the upper, predetermined threshold at **515**, then the present invention can decrease the index in block **520**. The index from block **520** is then used in block **525** to obtain a rate and power pair from a rate and power table, such as that shown in FIGURE 4. Alternatively, and/or in addition to the foregoing (as indicated by the dashed lines), the PER may also be compared to a lower threshold, as shown in block **540**. If the PER is not below the lower, predetermined threshold, the present invention returns to **515**. However, if the PER is below the lower, predetermined threshold at **540**, then the present invention can increase the index in block **545**.

In other embodiments of the invention, shown in FIGURE 6A, SNR **630a** and PER **630b** are used as inputs **630**. The index into the table of FIGURE 4 is decreased when PER **630b** is above T_{PER} and/or when the SNR **630a** falls below a lower threshold. Likewise, the index of FIGURE 4 can be increased when SNR **630a** moves above an upper threshold. In some embodiments, one or both of the upper and lower SNR thresholds are a function of the transmit data rate, so each individual data rate will have its own set of upper and lower thresholds. As the rate increases/decreases, the thresholds of SNR **630a** will correspondingly increase/decrease.

FIGURE 6B shows an exemplary flow diagram for the embodiment shown in FIGURE 6A. A determination is made in block **615** as to whether or not the PER is above an upper, predetermined threshold (as discussed above relative to FIGURE 5B, PER may also be compared to a lower threshold). If the PER is not above/below the predetermined threshold, the present invention proceeds to **640**. However, if the PER is above/below the predetermined threshold at **615**, then the present invention can decrease/increase the index in block **620**. Additionally, a determination is made in block **640** as to whether or not the SNR is either above an upper threshold or below a lower threshold. If the SNR is neither above the upper threshold nor below the lower threshold, the present invention returns to **615**. However, if the SNR is above the upper threshold in block **640**, then the present invention

can increase the index in block **620**. If the SNR is below the lower threshold in block **640**, then the present invention can decrease the index in block **620**. The index from block **620** is then used in block **625** to obtain a rate and power pair from a rate and power table, such as that shown in FIGURE 4. In some embodiments, the rate selected in block **625** may be used in block **675** to select new thresholds for use in block **640**.

FIGURE 7A illustrates other embodiments of the invention, in which PER **730a** is taken as an input **730** along with an (SNR, SINR) pair **730b** as shown. The index into the table of FIGURE 4 is decreased when PER **730a** is above a threshold (e.g., T_{PER} above) and/or when the (SNR, SINR) pair **730b** indicates the current rate and power level setting can not be supported without an unacceptable level of packet errors (e.g., without exceeding the PER threshold). The lower and upper thresholds for use with the SNR/SINR pair **730b** are analogous to the use of the upper and lower thresholds with SNR **630a** in FIGURE 6 embodiments. The thresholds for the (SNR, SINR) pair **730b** can be precomputed for each possible rate. Likewise, the index of FIGURE 4 is increased when the (SNR, SINR) pair **730b** indicates that an increase in the index can be made without increasing PER **730a** above the PER threshold. In some embodiments, one or both of the upper and lower (SNR, SINR) pair thresholds are a function of the transmit data rate, so each individual data rate will have its own set of upper and lower thresholds.

FIGURE 7B shows an exemplary flow diagram for the embodiment shown in FIGURE 7A. A determination is made in block **715** as to whether or not the PER is above an upper, predetermined threshold (as discussed above relative to FIGURE 5B, PER may also be compared to a lower threshold). If the PER is not above/below the predetermined threshold at **715**, the present invention proceeds to **740**. However, if the PER is above/below the predetermined threshold, then the present invention can decrease/increase the index in block **720**. A determination is made in block **740** as to whether or not f(SNR, SINR) (a predetermined function of the SNR, SINR pair) is either above an upper threshold or below a lower threshold. If f(SNR, SINR) is neither above the upper threshold nor below the lower threshold, the present invention returns to **715**. However, if f(SNR, SINR) is above the upper threshold in block **740**, then the present invention can increase the index in block **720**. If f(SNR, SINR) is below the lower threshold in block **740**, then the present invention can decrease the index in block **720**. The index from block **720** is then used in block **725** to obtain a rate and power pair from a rate and power table, such as that shown in FIGURE 4. In some embodiments (as indicated by the dashed lines), the rate selected in block **725** may be used in block **775** to select new thresholds for use in block **740**.

FIGURE 8 diagrammatically illustrates exemplary embodiments of transmitting apparatus **210** of FIGURE 2. In FIGURE 8, communication application **805** sends and

receives communication information to and from packet processor **815**, which in turn exchanges packets with wireless communication interface (WCI) **820**. Packet processor **815** can use conventional techniques to packetize information bound from communication application **805** to WCI **820**, and to extract information from packets bound from WCI **820** to communication application **805**. WCI **820** can interface packet processor **815** to a wireless communication channel in conventional fashion. WCI **820** sends quality information **823**, such as conventionally available PER, SNR and SINR information, to joint rate and power controller **850**. Joint rate and power controller **850** assesses quality information **823** in quality evaluator **853**. The results from quality evaluator **853** are used to set index control **855.** Index control **855** will determine which rate **860** and power **870** pairs of table **857** (e.g., the table of FIGURE 4) are provided by joint rate and power controller **850** to control operation of WCI **820**.

FIGURE 5C illustrates exemplary embodiments of controller 850 of FIGURE 8. The embodiments of FIGURE 5C can perform the operations illustrated in FIGURE 5B. PER **530** is obtained from WCI **820**. PER **530** and a predetermined threshold (upper and/or lower as discussed above), T_{PER} **532**, are compared by comparator **580**. The result of that comparison is used to set index control **855** into table **857**.

FIGURE 6C illustrates exemplary embodiments of controller **850** of FIGURE 8. The embodiments of FIGURE 6C can perform the operations illustrated in FIGURE 6B. PER **630a** and SNR **630b** are obtained from WCI **820**. PER **630a** and a predetermined threshold (upper and/or lower as discussed above), T_{PER} **632**, are compared by comparator **680**. The result of that comparison is used to set index control **685**. In addition, SNR **630b** and predetermined SNR thresholds, T_{LOWER} **634** and T_{UPPER} **636**, are compared by comparator **670**. The result of that comparison is used to set index control **675**. Index controls **685** and **675** drive logic **660** to produce index control signal **855**, to determine which of the rate and power pairs of table **857** are sent to WCI **820**. In some embodiments (as indicated by the dashed lines), the rate selected from table **857** is used to select new thresholds from threshold table **695** for input to comparator **670**.

FIGURE 7C illustrates exemplary embodiments of controller **850** of FIGURE 8. The embodiments of FIGURE 7C can perform the operations illustrated in FIGURE 7B. PER **730a**, SNR **727**, and SINR **729** are obtained from WCI **820**. PER **730a** and a predetermined threshold (upper and/or lower as discussed above), T_{PER} **732**, are compared by comparator **780**. The result of that comparison is used to set index control **785**. In addition, SNR **727** and SINR **729** are processed at **730b** (e.g., used to access a look-up table) to form f(SNR, SINR). The f(SNR, SINR) **731** formed at **730b** are compared by comparator **770** to

thresholds, T_{LOWER} **734** and T_{UPPER} **736**. The result of that comparison is used to set index control **775**. Index controls **785** and **775** drive logic **760** to produce index control signal **855**, to determine which of the rate and power pairs of table **857** are sent to WCI **820**. In some embodiments (as indicated by the dashed lines), the rate selected from table **857** may be used to select new thresholds from threshold table **795** for input to comparator **770**.

The various threshold values described above, as well as the function, f(SNR, SINR), can be readily determined, for example, empirically through experimentation and/or simulations under expected operating conditions.

Although exemplary embodiments of the present invention have been described in detail, it will be understood by those skilled in the art that various modifications can be made therein without departing from the spirit and scope of the invention as set forth in the appended claims.